Use of Crop Models in Assessment of Soil Drought

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Summary

The aims of the study were to apply, test and to present the ability of the deterministic simulation models SIMWASER and CERES-Wheat computing soil-water balance components, percolation losses, ground water recharge and capillary rise. Two case studies for the assessment of percolation losses from irrigated carrots to deep groundwater at Obersiebenbrunn in the Marchfeld (Austria) and ground water recharge and capillary rise from shallow groundwater in grass lysimeters at Berlin-Dahlem (Germany) together with two test sites with similar climatic conditions and soil water storage potential but with (Grossenzesdorf, Austria) and without (Zabcice, Czech Republic) groundwater impact in a semi-arid agricultural area in central Europe were chosen. At Obersiebenbrunn, simulated percolation and evapotranspiration were 183 and 629 mm, while the respective measured values amounted to 198 and 635 mm. Up to 42% (194 mm) of evapotranspiration was provided by groundwater at s Grossenzesdorf and only 126 mm was used for the worst case comparing to observed data. These results showed both models as proper applicable tools to demonstrate crop – soil – water relations. However, the availability and management of soil water reserves will remain important, especially when extreme events such as droughts occur more frequently and annual soil and groundwater recharge decrease.

Key words

crop model; soil; water; drought

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Introduction

Modeling of interactions between plant-soil-water is one of the important steps how to improve crop management strategies. Soil water balance of cropping systems, involving detailed experimental field monitoring and simulation modeling already assists agronomists to offer improved management options for greater production, profitability and minimize risks to environmental degradation (e.g. dryland salinity soil erosion) (Zhang et al., 1999). Soil water balance means the regular interaction between precipitation and evaporation, run-off and storage-change in an area. Within the soil it means the temporal change of the water content of the soil due to resorption, storage and release of water. These are important factors for different usage, like water management (drinking water, etc.), planning of handling agricultural land or reflecting the effect of irrigation management strategies to yield (Colaizzi et al., 2003). According to that, simulation of water movement in agricultural soils has become a very valuable tool in estimating the amount of natural ground water recharge (Guber, 2000), which must be known for effective ground water use (Lilly et al., 2003) as well as for the quantification of ground water pollution by fertilizers and pesticides. The respective models must be tested extensively taking into account different climatic conditions together with variable soil conditions and they also should be able to run at least for the most important agricultural crops, in order to get realistic simulation results (Maraux and Lafolie, 1998; Šťastná and Žalud, 1999; Xie et al., 2001). Long time periods and intensive field measurements of the soil water balance at different places are therefore very important to gather the data needed for model calibration and verification (Mills, 2000; Cook and Dent, 1990).

The aim of this study was to present SIMWASER model (Stenitzer, 2003; Moreno et al., 2003) and to demonstrate its ability to simulate percolation to a deep groundwater and capillary rise from shallow groundwater. As the second part to highlight the critical water balance parameters and water stress situations for the selected cultivars under the present climatic conditions (1xCO_2 weather) and modified (2xCO_2) climate scenarios (combined effect) by model CERES-Wheat.

Material and methods

Model description

The functional and deterministic model **SIMWASER** was developed to describe one-dimensional, vertical flow of water in a soil profile. Inter-flow and preferential flow was neglected. Water balance and plant growth are linked together by the physiological interaction of assimilation and transpiration. The increase of dry matter production depends on absorption of carbon dioxide from the air via the stomata, during which process water vapour is lost from inside of the plant to the unsaturated air. As long as the delivery of water to the stomata can satisfy potential transpiration, potential assimilation and potential plant growth take place, otherwise stomata will close and dry matter accumulation will be restricted. All the abovementioned processes are influenced by the respective development phase of the plant, e.g. the partition of the daily-assimilated plant dry matter between leaves, stem and roots. SIMWASER defines the current development stage as quotient of the current accumulated 'growing degree days' divided by the sum of growing degree-days necessary for plant growth from sowing to ripeness. A 'growing degree day' is defined by the mean of daily air temperature minus a base temperature typically for the respective crop.

The actual plant growth is calculated from the potential production rate as the proportion of actual transpiration to potential transpiration (eqn.1).

$$Pact = Ppot*Tact/Tpot \quad (1)$$

Pact, Ppo - actual and potential plant production (kg CH_2O/m^2, d)
Tact, Tpot - actual and potential transpiration (mm/d)

Potential evapotranspiration PET is calculated according to the well known 'Penman- Monteith - formula" (eqn. 2):

$$PET = (ft*Q+0.864*H0/Rair)/(ft+1+Rcrop/Rair) \quad (2)$$

PET - potential Evapotranspiration (mm/d)
ft - weighing factor, depending on air temperature
Q - evaporation equivalent of available energy (mm/d)
0.864 - factor converting ((g H_2O/mł)/(s/cm)) to (mm/d)
H0 - saturation deficit of air (g H_2O/m^3 air)
Rair - aerodynamic resistance against water vapor exchange (s/cm)
Rcrop - crop resistance against water vapor exchange (s/cm)

The water balance on daily base is made at the soil surface with precipitation and irrigation as input and evaporation and transpiration as output. Interception is also taken into account. The water movement within the soil is calculated according to Darcy's Law and the 'continuity equation'. The soil profile is divided into several soil layers (usually of 5-10 cm depth) down to a depth in which plant roots may not have any direct influence on the water movement. In case where capillary rise from shallow groundwater must be taken into account the deepest soil layer must reach below the deepest groundwater level. In such case the boundary condition at the lower end of the model profile is given by the current groundwater level, otherwise the lower boundary condition is defined by the capillary conductivity of the deepest soil layer at the current water content. The 'normal' time step of the model is the day, but water movement is calculated using variable time steps, which are limited by the condition, that the maximum change of water content within any of the soil layer during the time step is restricted to 0.001 cmł/cmł.

The CERES (Crop Environment REsource Synthesis) - Wheat model (Ritchie and Otter, 1985) was designed to simulate the effects of cultivar, planting density, weather, soil water, and nitrogen on crop growth, development, and yield. There are four groups of input data necessary in order to prepare and run model simulation. The minimum data set of the weather data includes daily values of maximum and minimum temperature, global radiation and precipitation. Genetic coefficients were derived partly from literature sources and partly from experimental data from test sites. Soil input data were derived from soil pits that were situated directly at the experimental site. The grain yield has been selected as the evaluation parameter for CERES-Wheat model in both localities. To generate series representing changed climate conditions, the generator parameters were modified on the basis of the climate change scenario. The weather generator has been validated in detail in Dubrovský (1996, 1997) and was found satisfactory for use in the crop growth modelling. Recent transient runs of general circulation models (GCMs) were used to develop climate change scenarios (Dubrovský et al., 2005). Based on the results obtained, the GCM that best reproduced the present climate was selected to define the scenario ECHAM4/OPYC3 (ECHAM).

Two experimental fields were chosen for the study with CERES-Wheat model. The first one in Žabčice (latitude 49° 01´ N, longitude 16° 37´ E, and altitude 179 m above the see level) is located in the south part of the Czech Republic. The long term mean of yearly precipitation is 480 mm, the mean annual temperature is 9.3 °C. The second experimental field in Gross-Enzersdorf (Marchfeld), is located within the same climatic region (latitude 48° 12´N, longitude 16° 34´E, and altitude 153 m above the see level) in north-eastern part of Austria. The mean annual sum of precipitation is 577 mm and the mean annual temperature is 9.9 °C. Winter wheat (*Triticum aestivum* L.) was grown as an experimental crop at both localities: cultivar "Perlo" in Gross-Enzersdorf and cultivar "Hana" in Žabčice stations, in order to use experimental data for model validation. The soil type in Žabčice belongs to the subgroup Oxyaquic Cryofluvents (USDA Classification, 1975). The soil at the experimental field in Gross-Enzersdorf could be classified as the soil type 19 according to the Austria Soil Classification (ÖBK). The soil is described as chernozem on fine calcareous sediments over gravel and sand.

Input weather files were created to run the simulations in the selected locations. The observed weather data of the period from 1985-1993 were used for the simulations. For the 2xCO_2 weather the monthly changes in the relevant scenario were applied to the daily weather data. Winter wheat growth and development were simulated for two (a-b) various conditions: **(a)** present conditions (1xCO_2 weather, 330 ppm), representing no change in used weather input files (present climate) and in CO_2 concentration in the atmosphere (330 ppm), **(b)** combined effect (2xCO_2 weather, 660 ppm), representing a change in weather input compared with the present climate (according to scenarios) and in CO_2 concentration in the atmosphere (660 ppm). The obtained simulation results were analyzed to assess the impact of water balance and water stress to the endurance of wheat growing stages by Zadock (Zadock et al., 1974) as well as on photosynthesis and growth in these stages.

Case studies

The performance of the SIMWASER model in estimating percolation and/or capillary rise may be demonstrated by comparing measured and simulated results from field experiments and lysimeter studies. The following case studies are focussed on assessment of percolation losses from irrigation to deep groundwater and on estimation of capillary rise from shallow groundwater.

Percolation losses from irrigated carrots at Obersiebenbrunn in the Marchfeld (Austria)

The experimental field in Obersiebenbrunn is situated at 48° 15' N and 16° 41' E, at about 151 m above sea level with mean air temperature of 10.1 °C and 510 mm rainfall. The soil is a Chernozem [Calcic Chernozem according to ISSS 1994 (Spaargaren, 1994)] of about 90 cm depth, covering a gravelly aquifer with ground water surface at about 250 cm below soil surface: therefore no capillary rise to the rooted soil horizons will take place. The measuring site was instrumented systematically at 10 cm distance down to 160 cm with TDR-Sensors (TRASE system) to measure soil water content, and with calibrated resistance blocks (BECKMAN gypsum blocks and WATERMARK granular matrix sensors) to measure soil water suction. Soil temperature was also measured systematically at different depth for correction of the resistance block readings. Physical soil parameters (pF- and Ku-curves) were determined by undisturbed soil samples in the laboratory. Additionally 'field-pF-curves' were established by analysing concurrent measurements of water content and suction at the measuring site. The combination of both, laboratory and field pF-curves, was used for simulation. Measured capillary conductivity was extrapolated according to the shape of the resulting pF-curve by the method of Millington & Quirk (Klute, 1986).

Percolation was deduced from systematic measurements of soil water content and soil suction according to DARCY's law (eqn. 3):

$$perc = K(w)*I \tag{3}$$

with

perc = percolation flux (mm/d)
K(w) = capillary conductivity at water content (w) at 140 cm depth
I = suction gradient at 140 cm depth

For the case study presented here deep percolation from irrigated carrots in the year 2002 is investigated. Monthly mean values of measured soil water storage and percolation on the experimental field as well as calculated evapotranspiration have been analysed.

Ground water recharge and capillary rise in grass lysimeters at Berlin-Dahlem (Germany)

The lysimeter station at Berlin - Dahlem consists of 12 weighable lysimeters, by which all components of the soil water balance may be measured (Zenker, 2003). The station is situated at 52° 28' N and 13° 18' E, at about 51 m above sea level with mean air temperature of 9.3 °C and 545 mm rainfall. The lysimeters have a surface of 1 m$_{ \text{\textcent} }$ and they are 150 cm deep; they contain three different types of undisturbed soil monoliths. All lysimeters were under grass from 1996 to 1999 and had a constant ground water level at either 210 cm ('deep ground water') or 135 cm depth ('shallow groundwater'). For the case study presented here, simulation was restricted to one year (April 1997 to March 1998) and only lysimeters No. 3 and 4 were investigated, which represent a sandy Humic Podzol (ISSS, 1986) from Wildeshausen (Lower Saxonia, Germany), with shallow ground water depth.

Results and discussion

At the Obersiebenbrunn experimental field simulated soil water storage and simulated fluxes of evapotranspiration and percolation are in good agreement with the measured values. Simulated accumulated percolation and evapotranspiration during the vegetation period amounted to 183 and 629 mm respectively, which is close to the measured values of 198 and 635 mm.

At the Berlin - Dahlem station measured and simulated values of soil water storage, fluxes of capillary rise, and evapotranspiration agree very well also. Here simulated accumulated percolation and evapotranspiration during the vegetation period were -122 and 458 mm, whereas measured values were -115 and 454 mm.

A significant observation from this work is the value of using an integrated and realistic model. Such model as SIMWASER may be used to integrate point measurements within a real-time basis for water content, pressure-head and water-level changes. This study also identifies practical field instrumentation and analytical model for estimating ground-water recharge using real-time databases. It is able to demonstrate temporal relationships in subsurface water flow, water-content redistribution and evapotranspiration.

Graphical comparison of measurements and simulation results for both case studies shows that SIMWASER model is able to simulate the percolation and capillary rise with rather good accuracy, thus prooving this model as a valuable tool in soil hydrology research at the field scale. We will be focused on evaluation of drought risk, soil water balance, and soil processes in agricultural land use, crop growth, and yield in the field study, which is going to be done in Zabcice experimental station (the Czech Republic) soon. In such case it is necessary to have a good assessment of soil water availability to predict yields more correct, since it is known that soil water balance influences crop during a growing period. SIMWASER model will be used in the mentioned study to prove its eligibility to simulate so influence of water availability on crop yield.

The model Ceres-Wheat was validated using observed and simulated grain yields for the years 1985 to 1993 after successful calibration at both locations with coefficient of determination 0.73 and standard deviation 582 kg ha^{-1} for Žabčice ("Hana" winter wheat cultivar) and with coefficient of determination 0.76 and standard deviation 696 kg ha^{-1} for Gross-Enzersdorf ("Perlo" cultivar). Simple linear regressions were computed to determine the R^2 value between observed and simulated data and the simulated yield percentage within 10 per cent of the observed yield.

To show the impact of soil water balance and water stress on wheat yield for particular growing stages for both localities, yields and water stress values 0-1 (0 – no water stress, 1 - the highest water stress) for the years 1985-1993 were simulated by CERES-Wheat model.

Present conditions (1xCO_2 weather, 330 ppm) showed following results: Simulated rain-fed winter wheat yield values varied by around 3000 kg ha^{-1} at both locations, if no groundwater impact was assumed, which is less than half of the simulated potential yield (no water stress) of about 6600 kg ha^{-1} at both sites. Such low yields occurred because of significant water stress during most growing stages. One of the reasons for the high water stress levels during the growing period was the low initial soil water content of winter wheat in autumn, which was set at the wilting point to show more clearly the reaction of winter wheat to water deficit under extreme conditions. These conditions are realistic for Gross-Enzersdorf in some years, but not for Žabčice, where groundwater has an impact on the rooting zone. When groundwater impact was simulated at Žabčice, the yield under rain-fed conditions (6571 kg ha^{-1}) came close to the potential yield for that site due to only very low water stress during all phenological stages. The duration of the simulated total growing period, based on the real local conditions, differed by 37 days between the two sites, caused only by the difference during winter dormancy (Zadock´s stage 0-30). Also, the sowing date in autumn was set 10 days earlier at Žabčice.

Combined effect (2xCO_2 weather, 660 ppm): increased CO_2 concentration affects wheat growth directly through stimulation of photosynthesis, reduced transpiration and improved water use efficiency, as e.g. reported by Rosenberg et al. (1990). Rain-fed yield was simulated and the best results in terms of absolute yield and less water stress being obtained with the ECHAM scenario at Žabčice (groundwater impact, 7496 kg ha^{-1}) at Gross-Enzersdorf (3806 kg ha^{-1}). There was no indication of water stress at any growing stage for the groundwater impact case at Žabčice. The total growing period at Žabčice decreased for 31 days on average for the scenario compared with present conditions, but this was caused only by the shortened winter dormancy period (represented by Zadock stage 0-30). As no water stress occurred, the simulated yields were relatively high (7455 kg ha^{-1} average), almost the level of potential yield, and increased for 13.5 per cent compared with the present weather case. Assuming no groundwater impact at Žabčice, the rain-fed yield increased for 52.5 per cent to only 5496 kg ha^{-1} on average for all scenarios. At the Austrian location (Gross-Enzersdorf , no groundwater impact) rain-fed yield was lower than for the same case (without groundwater impact) at Žabčice. Water stress at Gross-Enzersdorf occurred regularly during the growing period and the yield increased for about 39.1 per cent with a reduction in winter dormancy of eight days (Zadock stages 0-30) on average. Except for the ECHAM scenario at Gross-Enzersdorf, the highest increases in yield compared with current conditions were found for the combined effect at both locations in cases where there was no groundwater impact. However, at Žabčice the highest absolute yields were obtained with groundwater impact.

The main explanation of continuously higher water stress levels at the Austrian location (and by that a stronger decrease of grain yields) compared to Žabčice with groundwater impact is related to differences in the soil water balance during the winter wheat growing period, as there is no ground water impact to the rooting zone in Gross-Enzersdorf. The comparison between total biomass accumulation and soil water balance at both experimental sites shows a big difference between the two sites. Through much lower initial available soil water storage in Gross-Enzersdorf with no impact from groundwater, soil water deficit occurs faster despite the total precipitation amount is higher than in Žabčice and its distribution is very similar.

The average lower soil water storage during the growing period leads to less biomass accumulation and lower transpiration through frequently occurring drought stress together with no drainage, low runoff and higher evaporation (less biomass and ground cover) in Gross-Enzersdorf. Žabčice in contrast has much higher soil water storage in the rooting zone through the impact of groundwater, which can act as a buffer during drought periods.

Yields and water stress values 0-1 (0 no water stress, 1 the highest water stress) for period from 1985 to 1993 simulated by the CERES-Wheat model with the modified weather files from the ECHAM scenario (combined effect) were chosen to show the impact of soil water balance and water stress on wheat yield for particular growing stages for both localities. ECHAM shows a strong decrease in precipitation in April of 20 %, which highlights potential water stress effects during this critical month under changed climate. During the first Zadock´s stage only low water stress (less then 0.1) occurred at either locality, and this stress level did not influence the final wheat yield, although Žabčice recorded this stress every year except for 1990. During the second stage, very high water stress occurred in 1989 and 1991 at Gross-Enzersdorf compared with Žabčice, where only low stress occurred in 1988. However, high values at this stage did not have a significant impact on the grain yield as well (e.g. high water stress level, but also high yield in 1991). Simulated water deficit appeared also during the third stage at Gross-Enzersdorf, where the water stress values reached 0.7 in 1989 and 1993.

The most yield-sensitive growing stage was during the grain-filling period at Gross-Enzersdorf (the fourth and especially the fifth Zadock´s stage), which can be seen by comparing the yield and water stress levels in 1990 and 1991. The highest water stress indicators correspond directly with the lowest yields (1990 and 1993) for the whole nine-year period. In general, high water stress values during 1990 and 1993 caused very low yields, but the mean stress value in 1989 and 1991 did not significantly influence the yield, because of a lower water stress level during the grain-filling period. This result confirms the different sensitivity of winter wheat growing stages to water stress occurrences that has been demonstrated experimentally (Kastelliz and Ruckenbauer, 2000). The continuously higher water stress levels at the Austrian location (and hence a greater decrease in grain yields) compared with Žabčice can be explained by differences in the soil water balance during the winter wheat growing period. Because of the much lower available soil water at Gross-Enzersdorf, soil water deficit occurred faster, despite the fact that total precipitation was higher than at Žabčice and the distribution was very similar (not shown).

There was also no drainage, low runoff and higher evaporation (less ground cover). Žabčice, by contrast, had much higher soil water storage in the rooting zone by the impact of groundwater, which can act as a buffer during drought periods. Total biomass accumulation and yield was therefore significantly higher at Žabčice for rain-fed conditions as no water shortage occurred in spite of increased soil water use. At Žabčice negative values are shown for the winter wheat growing period, which would represent the input of groundwater, if we assume no change in soil water storage on a year-to-year basis. It was 194 mm during the growing period under present conditions and 126 mm for the ECHAM scenario. The simulated hypothetical case of no groundwater impact at Žabčice (initial soil water content in autumn was set at the wilting point) highlights the importance of groundwater (or irrigation) for crop yields at that site for current conditions as well as under the applied climate scenarios. With no groundwater impact or decreasing groundwater table, rain-fed yield levels at Žabčice would decrease to levels similar to those at Gross-Enzersdorf. It also clearly shows the simulated increase of water use efficiency under 2xCO_2 scenarios: despite higher yield levels, crop transpiration significantly dropped compared to current conditions.

Conclusion

All agricultural sites with similar climatic conditions showed a simulated decrease in water stress and an increase in yields under future climate scenarios (combined effect of CO_2 increase in the atmosphere and change in weather) under the model assumptions and limitations. The impact of groundwater to the rooting zone showed strong impact on water balance and yield level at the site in Žabčice and is the main reason of the difference in yield levels between selected locations. There was found also a shortening of growing period for both sites under unchanged production technique. There is strong evidence, especially for soils with low soil water storage capacity or no groundwater impact to the rooting zone, that irrigation or water saving production techniques will remain their importance to reach the full production potential. These results showed both models as proper applicable tools to demonstrate crop – soil – water relations. However, the availability and management of soil water reserves will remain important, especially when extreme events such as droughts occur more frequently and annual soil and groundwater recharge decrease.

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